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THE PROBLEM OF EQUILIBRIUM IN THE WEIGHTLESS STATE

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16. Abstract
Study of the effect of weightlessness on the functioning of the vestibular apparatus of the inner ear. It is shown that the absence of gravity, particularly in combination with other accelerations, can lead to a number of physical and psychological disturbances in astronauts, since the organ of balance of the inner ear requires the presence of gravity as a stimulus to its proper functioning. The so-called space sickness can occur.

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THE PROBLEM OF EQUILIBRIUM IN THE WEIGHTLESS STATE

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The problem of equilibrium in the weightless state is extremely complex, and cannot be considered only as an isolated disorder of a specific organ. It is usually an interaction of various physical and psychological factors, which, in the absence of gravity, combine with individual differences and the effects of adaptation and training to produce greater or lesser pathological reactions in the astronaut. /139

However, no matter how complex the problem of equilibrium in weightlessness may be, we can immediately isolate certain factors directly linked to the lack of gravity which directly or indirectly cause general or localized reactions. Under weightlessness, the sensations of weight and pressure of one organ on another, to which the organism is adapted and accustomed, cease, and the hydrostatic blood pressure ceases as well. However, the change in the organ of equilibrium is the most significant. The function of this organ, the so-called vestibular apparatus of the inner ear labyrinth, is fundamentally upset, as it is directly connected to the force of gravity. It is also the main organ of equilibrium, although sight and kinesthesis (the deep sensitivity in joints and muscles) play an important role in this function as well. At least two of these three systems must function correctly in order to maintain equilibrium. Thus, if someone has a disturbance of the vestibular apparatus of the inner ear, he still manages to maintain equilibrium if vision and kinesthesis are preserved. However, if he finds himself in the dark, where his vision cannot serve him, or if he is left without support and kinesthesis cannot function,

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he cannot maintain equilibrium but will stagger and fall.

Under space conditions, special phenomena occur with respect to maintaining equilibrium. First, the organ of equilibrium in the inner ear is left without gravity, a basic stimuli for its effective functioning, and second, the absence of weight results in floating and loss of firm ground support, so that kinesthesis in joints and muscles cannot always play its part in maintaining equilibrium. Since under specific conditions of such a flight, other stimuli can occur which either compensate for or disturb the imbalance due to lack of earth gravity even more, one must know about the function and disturbances of the equilibrium organs during shorter as well as longer flight conditions.

The vestibular apparatus performs the function of equilibrium /131 on purely mechanical principles, and is found in its simplified, primitive form in less advanced animal species that are suitable for describing the principle of its function. For example, certain kinds of small shrimp have a small opening, called a statocyst, lined with hairy sensitive cells (Fig. 1.). In this statocyst can be found small grains of sand placed there by the shrimp itself, which, through their pressure, inform him of what is above and below. If, during motion, the grain changes place, it is a signal to the shrimp that he is leaning on one side, and by a specific movement of his body he immediately returns to equilibrium. If we

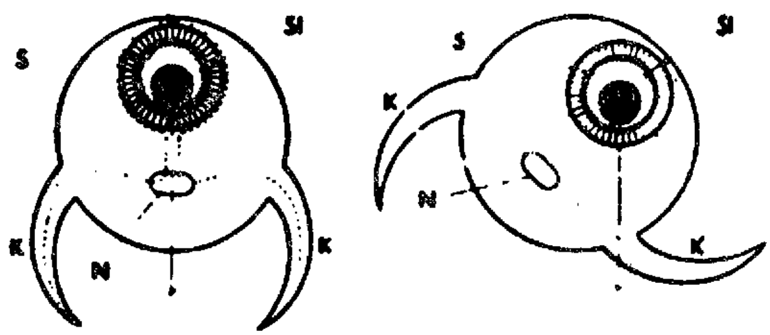

Fig. 1

remove the sand grains, the shrimp are completely disoriented and cannot move or maintain equilibrium. But if instead of sand grains, iron scale is inserted and the shrimp is exposed to the effect of a strong magnet, he orients himself toward the magnet as if it were gravity, depending on the direciton from which the magnet acts. This simply illustrates the way primitive animal species maintain equilibrium.

A part of the human equilibrium organ which reacts to linear accelerations has a very similar construction and function (Figs. 2 and 3). In the inner ear there are two small bags filled with liquid and on their walls are small islets (protrusions) of sensitive cells with short feelers placed in horizontal and vertical planes. There is a gelatinous mass above the feelers, on top of which is a layer of small crystals of calcium carbonate, crystallyzed in the shape of calcite, 1-10 microns in size. These crystals are three times heavier than the surrounding liquid (Figs. 3 and 4). As these islets are placed in different planes, the small pieces of crystal called otoliths or otochons will exert pressure on the feelers at each position of the head and supply information about gravity and other linear forces through the cells and nerve tissues, thus helping to maintain orientation in space, and also through muscle reflexes, to maintain the equilibrium of the body.

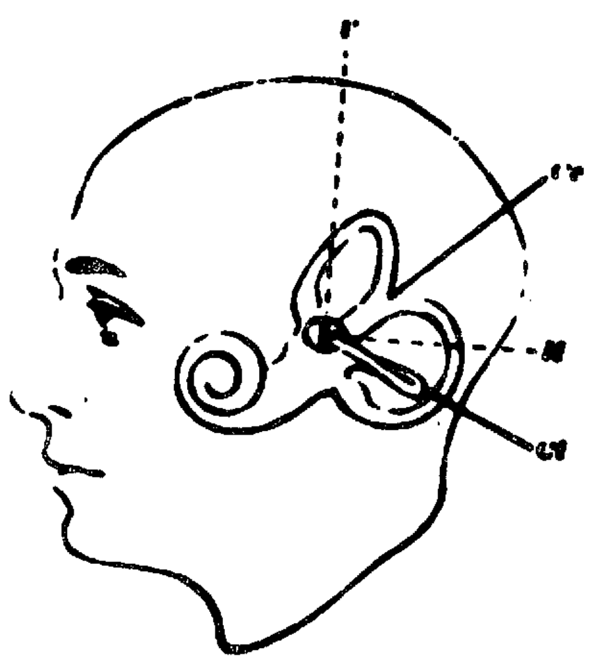

Fig. 2

Otoliths in the two pouches of the inner ear -- the utricle and the saccule --

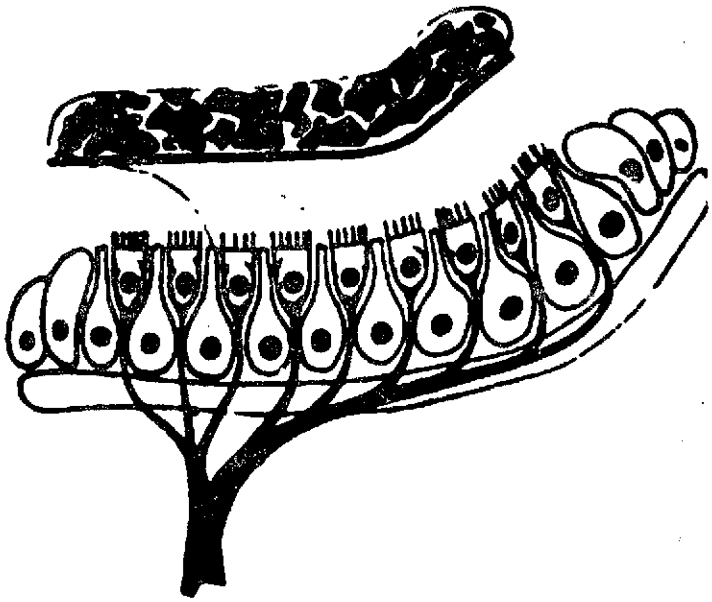

Fig. 3

correspond entirely in significance and function to the grains in shrimp described earlier. Besides gravity, all linear forces affect them and, depending on the direction of acceleration, an increase or decrease of otolith pressure on feelers of sensory cells occurs. As a function of that, the electrical discharge in cells also changes, and is transmitted to brain centers which, through muscle reflexes, perform instantaneously purposeful movements of the extremities and body in order to maintain equilibrium.

The effects of different directions of acceleration on the increase and decrease of otolith pressure on sensitive cells can /133
be seen in Figs. 5 and 6. Under normal living conditions on earth, the otoliths always exert pressure on some of these macules with sensory cells placed in different planes. The presence of this pressure results in tonal impulses indispensible for the necessary muscular tension in the human extremities and body. This tension varies within certain limits in the amount necessary to always maintain equilibrium while standing or moving.

Fig. 4.

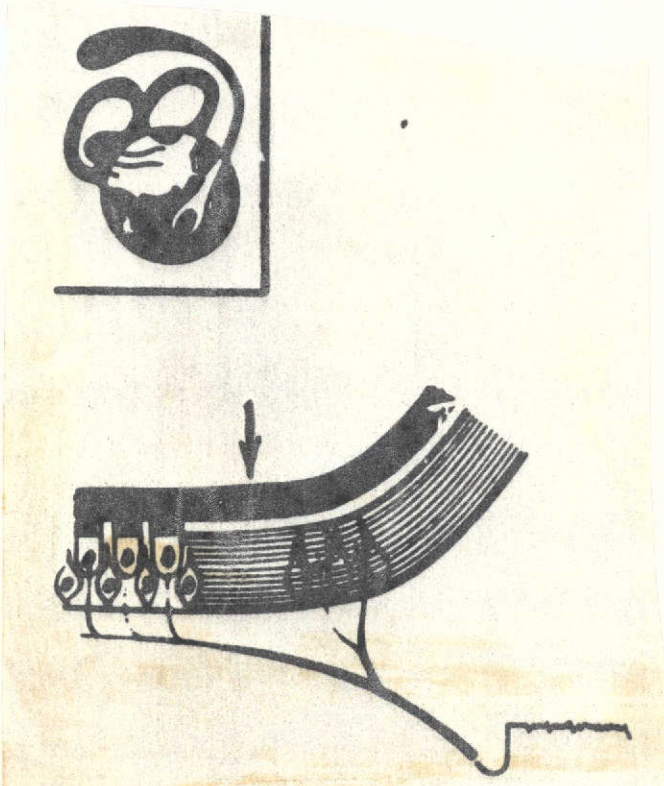

Fig. 5.

One of the basic effects of staying in the weightless state is the lack of otolith pressure on sensory cells in the macules of the static part of the equilibrium organ of the inner ear, and consequently the cessation of tonic action on the normal muscle tension of the body and of the extremities. This is manifested in inexperienced persons first as a falling, sinking or floating sensation accompanied by a feeling of instability and fear of falling, and a series of physical and psychological disturbances. With training, an astro- /134
naut adapts quickly to such a change of state and these pathological reactions disappear rapidly. However, the decrease in muscular tonus acts very adversely on the muscles if the stay in the weightless state is extended. A constant tension and performance of certain tasks are necessary for

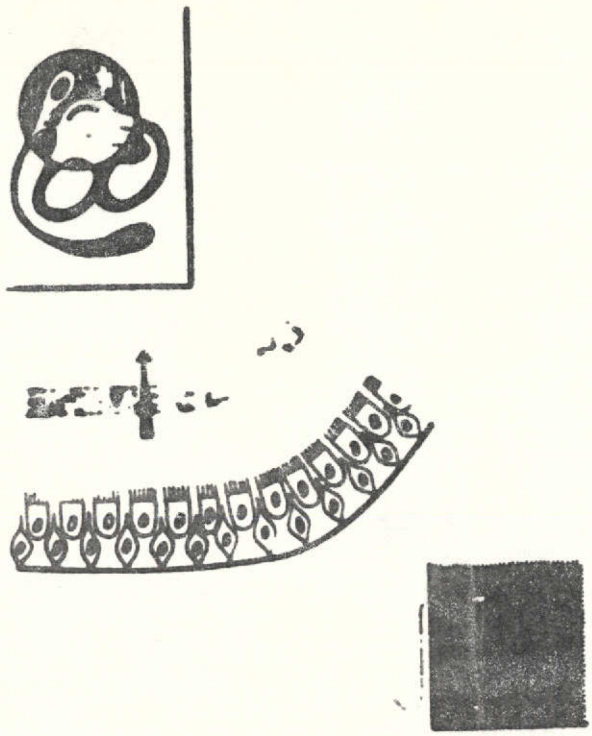

Fig. 6

muscle conditioning, and in the weightless state this is reduced to a minimum or it ceases completely. This is why the muscles lose power, shrink and become atrophies. In view of this, just after a one week stay (in space) a considerable muscle weakening occurs and a longer stay can make a person so weak that he is almost unable to stand up after returning to normal conditions of gravity. This has been noted in certain astronauts who spent a long time in a space ship. In order to somewhat alleviate these symptoms, the astronaut must perform specific exercises during a prolonged trip in a weightless state.

Besides a general weakening of muscles, the loss of speed and quality of muscular reflexes linked to the vestibular apparatus which have the function of maintaining the body support, are of particular importance for equilibrium. These reflexes are increasingly weakening as inactivity increases, so it is indispensible to provide for suitable exercises to maintain proper reflexes in the astronauts. However, in this regard, proper and adequate results can be attained only when artificial acceleration is achieved for simulating gravity.

In a weightless state there is a danger of erroneously stimulated impulses, which in the absence of otolith pressure on sensory cell feelers can easily occur. In addition, the least head movement can easily change the direction of the otolith's effect and thus result in a feeling of dizziness, causing space sickness. This happens particularly when the semicircular canals, which in addition to the utricle and saccule form the vestibular apparatus, are stimulated.

The three semicircular canals originate from the pouches, or utricles described earlier. Unlike the sensory cells in the macules of the utricles and saccules, which react to linear accelerations, the system of semicircular canals is suitable for registering angular accelerations. The semicircular canals, with the utricle from which they originate, form three closed rings in three dimensions (Fig. 2). They are filled with liquid which, due to /135
inertia during angular acceleration of the head (Fig. 7, arrows 3 and 4), will cause the movement of liquid in relation to the canal walls (arrows 1 and 2), depending on the plane where it is happening, resulting in a feeling of turning in space. The movement of the liquid is directly proportional to the angular

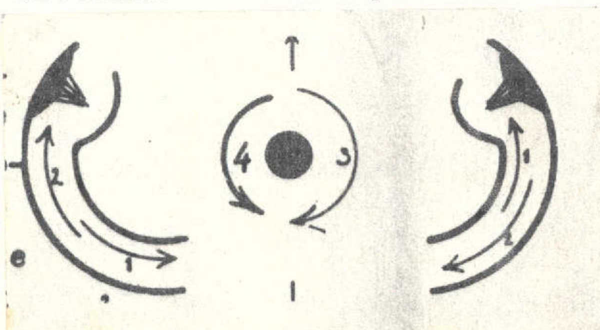

Fig. 7

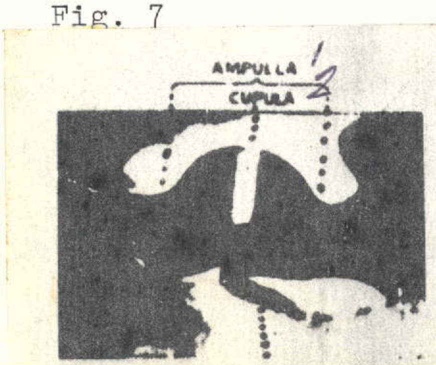

Fig. 8

acceleration and is registered in the expanded part of the corresponding canal called the ampulla (Fig. 8). The sensory system in the ampulla functions with a valve system, which is a mechanical system calculated for maximum efficiency in these relatively small movements of liquid. The ampullar widening is in reality located on only one side of the canal wall, in the shape of a semicircular arch. It took a long time to discover the reason for such a widening of the canal; namely, it is indispensible for the basic function of registering the movement of liquid in the canal. In a non-widened canal, during the

12 shows the actual distance between the top of the cupule and the arch of the ampulla which permits movement with considerable friction. This is important because in certain disturbances of the vestibular apparatus, there is considerable accumulation of liquid in the labyrinth, and as a result of the canal and ampulla enlargement, its arch moves away and the cupule loses contact with the arch. Due to the cessation of friction, the cupule bends considerably and by this causes severe attacks of dizziness. /137

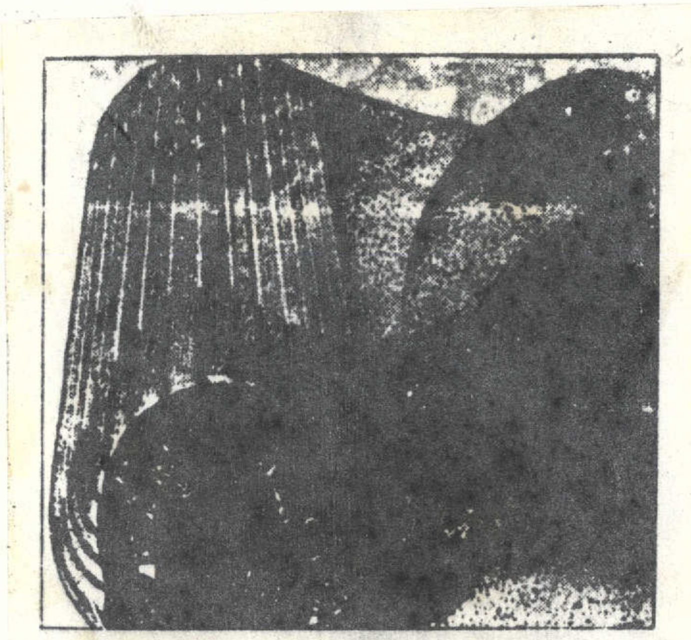

Fig. 10

Under space conditions, the functional disturbance of the vestibular apparatus occurs because of combined unnatural stimuli in both parts of the equilibrium system. Specifically, this occurs in the macules of the utricle and saccule because of a lack of otolith pressure due to the cessation of earth gravitational pull, and in the semicircular canals because of over-stimulation due to the coriolis acceleration. A complex of symptoms starts occuring, known as space sickness. In the manner it starts and in its symptoms, it greatly resembles air and sea sickness, except that under space conditions the duration of stimuli and the difficulty in removing the pathological effects are by far a greater problem. Persons with a destroyed vestibular apparatus do not suffer from space sickness, which shows that it is the essential stimulated organ from which the sickness starts. Simi- /138
larly, the astronauts who undertake special training for adaptation to conditions of space flight do not suffer from it. Untrained persons with normal sensitivity of the vestibular apparatus,

especially those with a greater sensitivity of the equilibrium system, would have great difficulties under space conditions.

As we have already mentioned, space sickness occurs as a combined effect of lack of gravity and coriolis acceleration which occurs because during work and movement, the head is revolving around a different axis than the one the space ship is revolving around. In cramped conditions of the cabin, this is all extremely magnified, when the astronaut's previous physical conditioning becomes considerably weakened, due to the extended decrease in movement. It occurs particularly in individually sensitive and poorly adaptable persons. Dominant symptoms are dizziness and physical disturbances (nausea, vomiting, palor, perspiration, accelerated breathing and heart beat). At every movement of the head, the symptoms worsen. Because of this, such patients lie immobile, trying to fix their sight on one point in order to reduce the feeling of dizziness. The duration of symptoms depends on adaptability and the measures taken. It is particularly important to take preventive measures to avoid the occurence of sickness. The astronauts must be examined thoroughly in the selection process, then be subjected to a long and intensive training of their vestibular apparatus, and finally be trained in a manner of movement in the cabin such that the coriolis acceleration will be reduced to the lowest possible degree. This does not mean that the astronaut's

Fig. 11

movements in the ship should be curtailed, as deliberate, short, straight-line movements have a beneficial effect on the vestibular apparatus, because they stimulate the otoliths and at least briefly simulate earth gravity, therefore contributing to the prevention of space sickness. Certain drugs can decrease the sensitivity of the vestibular apparatus. These drugs should eventually be taken even during the flight and the astronauts should be reminded to perform precisely certain movements. In larger ships of the future, where artificial gravity will be produced by appropriate rotation, thus reducing the possibility of space sickness, it will certainly be necessary to take care of the type of movements.

Fig. 12

In addition to space sickness caused by acute impairment in functioning of the vestibular apparatus, an extended flight in weightless state also causes a general reduction of muscular strength and atrophy as well as a change in the bones, because of reduced tonic tension. This can be prevented by proper exercise; otherwise, upon landing on earth there will be greater difficulties in the statics and dynamics of the body.

Conclusion

The problem of equilibrium in the weightless state is very complex. Disturbances of this function occur most frequently during the simultaneous action of different physical and psychological factors, which under particular conditions of absence of gravity can provoke greater or lesser pathological reactions in the astronaut's organism. The vestibular apparatus of the inner ear plays the dominant role in this. It reacts to linear and

and angular accelerations of the head and supplies information about changes in movement and speed in space. The vestibular apparatus is so adapted to the influence of the earth's gravity that gravity's shorter or longer absence, particularly when combined with other accelerations, can cause disturbances in the mechanics of equilibrium, as well as in the statics and dynamics of the astronaut's body. In order to prevent aftereffects, the mechanisms of this disturbance should be known.

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